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COMMON PARALLEL THERMOCOUPLES FOR AVERAGE TEMPERATURE MEASUREMENT

Bernard C. Boggs

Flight and Engineering Test Division

NOVEMBER 1960

WRIGHT AIR DEVELOPMENT DIVISION

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WADD TECHNICAL REPORT 60-650

COMMON PARALLEL THERMOCOUPLES FOR AVERAGE TEMPERATURE MEASUREMENT

Bernard C. Boggs

Flight and Engineering Test Division

NOVEMBER 1960

Project No. 1347
Task No. 13730

WRIGHT AIR DEVELOPMENT DIVISION
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
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FOREWORD

Investigations using parallel thermocouples in thermal simulation were conducted in support of Project No. 1347, ''Structural Testing of Flight Vehicles,'' Task No. 13730, ''Thermal Simulation Techniques.'' Work was accomplished during the period of February to April 1960 under the direction of Bernard C. Boggs, project engineer. Mr. Harold Hendrickson assisted in the analytical work and circuit-balancing techniques, and Mr. Helmut Ostrowski conducted the test surveys and reduced and assembled the test data.

ABSTRACT

This report describes the use of common parallel thermocouple circuits for temperature control in thermal simulation. Iron-constantan thermocouples were welded directly to the basic metal being heated. Structural tests at elevated temperatures show that thermocouples connected into parallel electrical circuits and grounded to a common metal sheet give the same temperature measurements as separated thermocouples connected into a parallel circuit. This method is applicable to any test situation requiring average temperatures.

COORDINATION SHEET

Prepared by:

Bernard C. Boggs

BERNARD C. BOGGS
Chief, Facility and Operation Unit
Strength Section, Structural Branch
Engineering Test Division
Flight and Engineering Test Group

Concurred in:

Carl E. Reichert

CARL E. REICHERT
Asst. Chief, Engineering Test Division
Flight and Engineering Test Group

Concurred in:

Hugh S. Lippman

HUGH S. LIPPMAN
Technical Director
Flight and Engineering Test Group

Approved by:

J Davis, Jr.

JOSEPH DAVIS, JR., Col, USAF
Commander
Flight and Engineering Test Group

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ILLUSTRATIONS

ILLUSTRATIONS (Continued)

LIST OF SYMBOLS

A	Designation for constantan thermocouple wire
B	Product of emissivity and Steffan-Boltzmann Constant
B	Designation for iron thermocouple wire
BTU	British Thermal Unit
c	Specific heat of material
C	Designation for constantan thermocouple wire
dT_s/dt	Derivative of surface area temperature with time
$E, E_o, E_1, E_2, E_3 \ldots\ldots E_N$	Electrical signal (volts)
Δe_1, Δe_2	Error signal (volts)
E_P	Calculated emf average
emf	Electromotive force
f( )	Function
Fe	Designation for iron thermocouple wire
G_1, G_2	Gain signal
h	Convective heat transfer coefficient
$I, I_1, I_2, I_3 \ldots\ldots I_N$	Current (amps)
K	Constant for circulating emf's
N	Number of terms
Q, Q_1, Q_2, Q_3, Q_1'	Heat input or heat required per unit area
q	Heat loss
r_1, r_2, r_3	Weld resistance or equivalent internal battery resistance
$R, R_o, R_1, R_2, R_3 \ldots\ldots R_N$	Resistance (Ω ohms) $R = R_T$
T_{aw}	Adiabatic wall or recovery temperature
T_s	Skin or area temperature
$T_1, T_2, T_3, \ldots\ldots T_N$	Measured (thermocouple) temperature, or calculated

LIST OF SYMBOLS (Continued)

T_E	Measured average electrical signal converted to temperature
T_M	Arithmetic mean temperature
T_P	Calculated temperature for parallel grounded thermocouples
w	Specific weight of material
Y	Power constant
n	Radiant heat efficiency factor
τ	Material thickness in feet

SECTION I

INTRODUCTION

In thermal simulation, we must know the temperature of the entire heated surface. If the surface is at constant and uniform temperature, only one temperature value would be needed to define the area; this condition, however, is too rare in actual temperature simulation to be considered.

The thermocouple provides an accurate and economical method for recording temperatures and for controlling the power required to heat a given surface area. Only one thermocouple has been used heretofore because no practical means existed for electrically insulating the thermocouples from the material being heated. For best control and computer operation, this single thermocouple has been located at the hottest known point in the area. Additional thermocouples, however, have been required to establish the hottest location, determine the temperature distribution, and monitor the tests.

In the past, a normal test installation consisted of a control thermocouple and a spare in each control area. Loss of the control thermocouple, in most instances, would abort the test; a switching device would enable the spare to regain test control. Thermocouples connected in parallel to a common junction, on the other hand, would provide a mean area temperature and eliminate the problem of test abortion.

Two methods of thermal simulation were presented in Reference 1, but the use of common parallel thermocouples in approximating a mean surface area temperature was not explained or substantiated. Of the three circuit combinations shown in Figures 51, 52, and 53 of Reference 1, the multiple ground connection (shown in Figure 52) is the most practical method and is repeated here as Figure 2. Test results reported herein show that this circuit with a suitable switching panel will permit each temperature measured by each thermocouple in the parallel circuit to be recorded individually and an average temperature feedback signal to be transmitted to instruments or equipment for regulating power or as a computer error feedback signal. Removing one thermocouple from the circuit temporarily for recording data will not alter the power requirements sufficiently to change the over-all temperature distribution or average feedback signal.

The number of thermocouples used in a given area must be governed by practical considerations. Enough thermocouples should be installed to provide a representative average temperature of the heated area. Since a full-scale elevated-temperature structural-test program of a present-day aircraft might require several thousand thermocouples for complete coverage, the total number must be limited by the type of simulation required.

This report presents analytical calculations for analogous DC battery circuits and summing circuits. Actual test data is presented and discussed for several combinations of materials in paralled thermocouple circuits. Although some basic theory is mentioned with respect to this application, these laws are not extended and treated separately for grounded parallel thermocouples. The primary effort consists of showing from the tests that the application is sound and the results are the same as for electrically separated thermocouples.

SECTION II

THERMOCOUPLE CONTROL SIGNAL FUNCTION

The thermocouple acts as a remote device for providing the thermal inputs to the test structure through the error feedback signal to a heat rate computer or as a control signal to a power regulator. The heat rate computer solves either of two fundamental equations for a unit area:

$$Q_1 = h(T_{aw} - T_s) - BT_s^4 \tag{1}$$

or

$$Q_2 = cw\tau(dT_s/dt) \ , \tag{2}$$

which is related to

$$Q_3 = YEI \tag{3}$$

in an equivalent radiant heat simulation. The computer must satisfy the equation $Q_1' = h(T_{aw} - T_s) - BT_s^4 + q$. The term q (BTU/ft^2/hr) indicates heat loss under test conditions. The control signal (volts) is then represented:

$$\Delta e_1 = G_1 \left[\left[h(T_{aw} - T_s) - BT_s^4 + q \right] - YEI/n \right] \tag{4}$$

or

$$\Delta e_2 = G_2 \left[\left[h(T_{aw} - T_s) - BT_s^4 - cw\,\tau_x \Delta T_s/dt \right]\right] \tag{5}$$

These equations represent requirement for unit areas, and thermal equilibrium must be achieved with T_s only, when solving for the instantaneous power required. T_s, therefore, is the only true test parameter and all other parameters are calculated and programmed into the computer to satisfy the remainder of the heat equation. The instantaneous skin or surface temperature, T_s, therefore, represents the mean temperature per unit area.

Whenever an area of several square feet is being heated, the temperature of a single point will not describe the temperature for the entire heated surface. The parallel thermocouple circuit provided the simplest and most economical method of obtaining the mean surface temperature for remote equipment.

Available literature indicated that parallel thermocouples require electrical insulation when connected to a common metal sheet. If uninsulated (or grounded to the basic material), it was believed that circulating currents between the individual thermocouples would introduce an error or alter the correct emf at the instrument connection. This effect was studied to determine the basic relationship of the circulating emf to the basic or primary emf. The thermocouple materials we use, including iron-constantan, Chromel-Constantan, Chromel-Alumel,* and platinum-platinum rhodium, produce up to 50 millivolts in their normal operating range. The iron-constantan thermocouples were used exclusively in these experiments.

* Trade name of Hoskins Mfg. Co.

SECTION III

PRACTICAL APPLICATION OF GROUNDED PARALLEL THERMOCOUPLES

The Law of Intermediate Metals and the Law of Intermediate Temperatures relate the theory of thermocouple emf's to temperature. We will not consider The Law of Intermediate Temperatures because the reference junction will not be involved; the effect between the measuring junctions cannot be accounted for as a separate part of the circulating emf's.

The thermal emf depends on the difference in temperature between the measuring and reference junctions and the wire materials used. The Peltier and Seebeck effect governs the emf resulting solely from contact of two dissimilar metals, and its magnitude changes with temperature; intimate contact is not essential, and the individual leads may be any distance apart. The temperature of each wire which represents the measuring junction circuit determines the magnitude of the emf. Most applications use wires either welded together or separated by small distances (approximately 1/4 inch or less) and welded to the material being measured.

The Thomson effect is that emf resulting from a temperature gradient along a single wire. While the Thomson effect can normally be neglected, it might be of interest in the area between thermocouple measuring junctions. Three different materials exist in the parallel circuit to produce an emf to the measuring instrument. Since temperatures are different in the areas between each measuring junction, and the temperature between each thermocouple varies, The Law of Intermediate Metals appears to have been violated. This law cannot be applied to solve this problem, however, because other factors enter and give redundancy.

Average temperatures can be measured from thermocouples connected in parallel. The equation

$$E_P = \frac{E_1 + E_2 + E_3 + \ldots E_N}{N} \tag{6}$$

may be written as

$$T_P = \frac{T_1 + T_2 + T_3 + \ldots T_N}{N} \tag{7}$$

from Figure 1. The actual conversion from volts to temperature occurs in the measuring instrument, and this term need not be carried in any of the equations.

In the application of common parallel thermocouples shown in Figure 2, the temperature along the line of measuring junctions may vary in any manner.

The equation for T_P is then:

$$T_P = \left[\frac{T_1 + T_2 + T_3 + \ldots T_N}{N}\right]_{AB} \pm f(T_{1,2};\ T_{2,3};\ T_{1,3}, \text{etc.}). \tag{8}$$

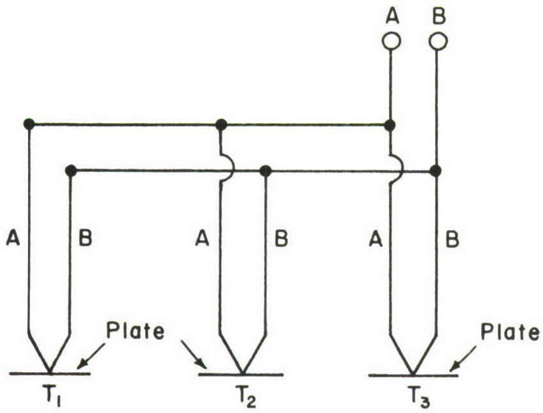


Figure 1. Separated Parallel Thermocouple Circuit

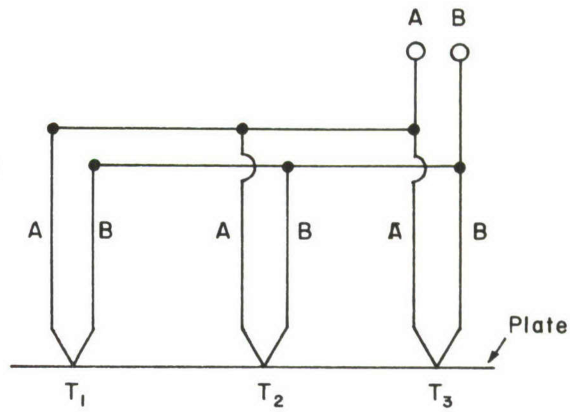


Figure 2. Common Parallel Thermocouple Circuit

In a separated parallel thermocouple circuit, individual thermocouples are thermally and electrically separated from one another at the measuring junction. In common parallel thermocouple circuits, each thermocouple is thermally and electrically connected at the measuring junction by a metal plate.

The second term is very small when all measuring circuits are physically attached to the plate and may be neglected. If any of one or several halves of the measuring circuit is broken, the equation then becomes

$$T_P = \frac{\frac{(T_1 + T_3)_A}{2} + \frac{(T_1 + T_2 + T_3)_B}{3}}{2} \pm f(T_{1,2}; T_{1,3}; T_{2,3}) \quad (9)$$

where A and B represent the individual thermocouple wire materials. Again, the second term is small and may be neglected in the calculation. In such cases, the measured signal in relation to the temperature is approximately equal to the calculated arithmetic mean:

$$T_P = T_M = \frac{(T_1 + T_2 + T_3 \ldots + T_N)}{N} \quad (10)$$

In instances where several thermocouples are paralleled and one material is removed from the measuring circuit at several locations, then the effect of the second term in

Equation (8) becomes a contributing factor at some point for any configuration. Under this condition, Equation (9) is used and the effect of circulating current must be considered. Even though the actual electric signal from the circuit is only slightly in error, the arithmetic mean calculation will show a big error. (Such conditions may exist during structural testing at elevated temperatures because thermocouple leads do break from various causes.) An empirical solution is necessary to define the contribution of the circulating currents, since it is impossible to determine true polarity at each point.

This method does not make a true temperature survey in the area between two measuring junctions. Extreme temperatures can exist without causing an appreciable change in the measured emf in most circuits. This application must be confined to averaging emf's from each measuring junction location.

The general theory developed from this application is that each material (A and B) may be considered separately as contributing to the total emf measured. In most instances the structure is grounded with the thermocouple circuit to the primary electric ground. It is possible, although impractical, to obtain fairly accurate measurements using one primary thermocouple wire material and a single wire ground material. Because of the relationship between A and B and B and A from one measuring junction to another in Figure 2, it appears that the total number of measuring circuits is N^2. Where no individual wire is broken, the cross-relationship is nullified and the resulting number of circuits is N. The average emf converted to equivalent temperature is the arithmetic mean of each thermocouple wire temperature. The circulating emf's are cancelled and, in general, the Seebeck and Thomson effects between each measuring junction are negligible.

SECTION IV

DC CIRCUIT FOR GROUNDED PARALLEL THERMOCOUPLES

For this analysis, each thermocouple measuring junction is considered as a battery. To simplify the calculations, only three are connected in a parallel circuit. The actual thermocouple weld resistance and the metal plate resistance were measured. These resistances are so small that they can normally be neglected. The weld resistance is in series and is included in the total resistance of each thermocouple circuit. The problem is simplified by combining all resistances for each circuit.

In a circuit of parallel batteries, the emf's are made equal with a change in equivalent internal resistances. Then, $E_1 = E_2 = E_3$, but $R_1 \neq R_2 \neq R_3$. Figure 3 shows the actual circuit, and Figure 4 shows an equivalent circuit.

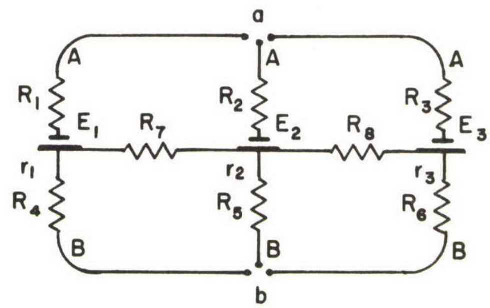


Figure 3. Electrical Circuit for Common Parallel Thermocouple Circuit

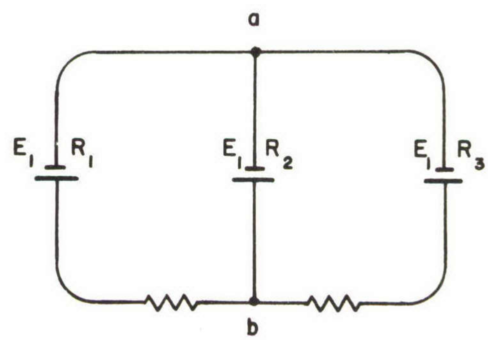


Figure 4. Equivalent Electrical Circuit Schematic for a Common Parallel Thermocouple Circuit

For practical considerations, an equal resistance will be added to each circuit and a total resistance assigned to each battery in the parallel circuit. Equal resistances are added in each circuit to minimize the effects of changes in thermocouple wire, weld, and plate resistances with temperature; an error is introduced if these resistances are unequal. Balancing each circuit by shortening or lengthening the wire of material having the higher resistance will serve the same purpose as adding resistors. Whatever method is used, each circuit should have the same resistance. The circuit analyzed is shown in Figure 5.

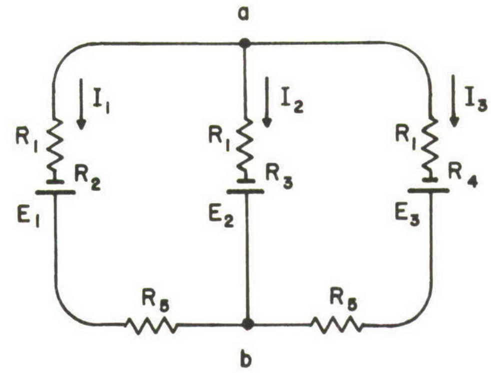


Figure 5. Electrical Parallel Thermocouple Circuit

A solution to R_5, which represents the resistance of the common metal plate material, can be found by employing Kirchoff's laws. Thermocouple spacing is equal and plate resistance between thermocouples is assumed equal. Then $E_1 = E_2 = E_3$ and:

$$-R_1I_1 + E_1 - I_1R_2 - I_1R_5 - E_1 + R_3I_2 + I_2R_1 = 0 \tag{11}$$

$$-R_1I_3 + E_1 - I_3R_4 - I_3R_5 - E_1 + R_3I_2 + I_2R_1 = 0 \tag{12}$$

$$I_1 + I_2 + I_3 = 0 \tag{13}$$

Solving for R_5 by simultaneous equations and substituting for the assumed conditions:

$$-R_5(I_1 - I_3) = 0 \tag{14}$$

when $I_1 = I_3$, which shows that the plate IR drop is nullified. The resistance R_5 is very small and, when I_1 is not equal to I_3, the difference is still insignificant. For most cases, then,the circuits in Figure 6 are applicable.

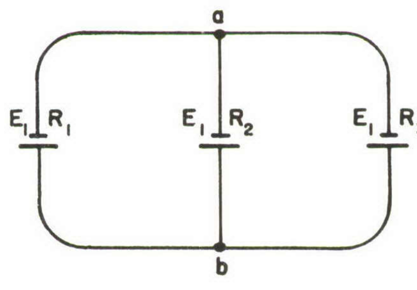


Figure 6A. Battery Circuit for Parallel Thermocouples

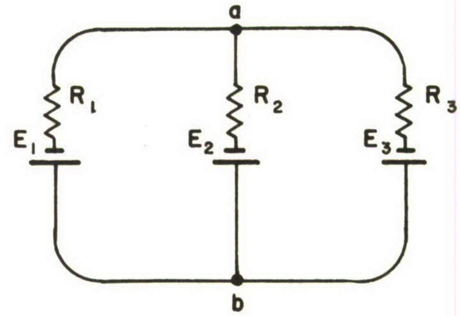


Figure 6B. Thermocouple Equivalent Battery Circuit

The basic equation for E_P is Equation (6). Since small changes in resistance would result from the variations in the temperature of the plate between the thermocouples, any variation in the bucking emf's will be small.

SECTION V

SUMMING CIRCUIT FOR GROUNDED PARALLEL THERMOCOUPLES

From the experiments, we concluded that a properly designed summing circuit could be used to parallel thermocouple measuring junctions. With such a circuit, a multitude of thermocouples could be connected in parallel on a common base metal to yield an emf representing the average for all points. In this approach, the base metal serves only as a neutral point in the circuits, and the emf's, as such, remain in the thermocouple wires leaving the base metal. The circuit resistance must be high when compared with the resistance of the thermocouple measuring junction.

Since the sum of all currents flowing to a junction must be equal to those leaving the junction, according to Kirchoff's first law, then the circuit shown in Figure 7 is analogous to a parallel thermocouple circuit with E_1, E_2, and E_3 indicating thermocouple voltage sources.

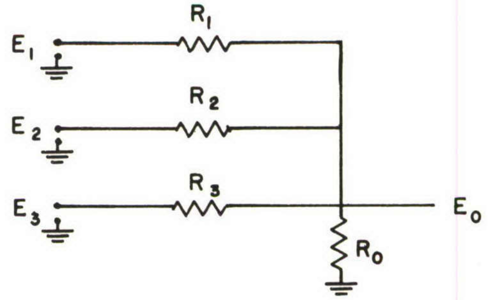


Figure 7. Equivalent Thermocouple Summing Electrical Circuit

If no current flows from E_o, the sum of all currents flowing to the output terminal must be equal to zero. Thus:

$$\frac{E_o - E_1}{R_1} + \frac{E_o - E_2}{R_2} + \frac{E_o - E_3}{R_3} + \frac{E_o - E_N}{R_N} - \frac{E_o}{R_o} = 0 \tag{15}$$

and

$$E_o = \left[\frac{E_1}{R_1} + \frac{E_2}{R_2} + \frac{E_3}{R_3} + \frac{E_N}{R_N}\right] \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_N} - \frac{1}{R_o}} \; . \tag{16}$$

If $R_1 = R_2 = R_3 = R_N$, and R_o approaches infinity, as a special case, then

$$E_o = \frac{E_1 + E_2 + E_3 + E_N}{R} \cdot \frac{1}{\frac{N}{R} - \frac{1}{R_o}} \; , \tag{17}$$

and Equation (17) reduces to:

$$E_o = \frac{E_1 + E_2 + E_3 + E_N}{N} \; . \tag{18}$$

Equation (18) is therefore the same as Equation (6), and equivalent to Equation (10).

The results of insulation versus no insulation are illustrated in Figures 8A and 8B. Two different approaches are presented for two thermocouples connected in parallel. Figure 8A depicts a circuit for a common plate and Figure 8B, a circuit for two separate plates. The diagrams present a series parallel circuit where the two emf's are additive in each series circuit (representing one thermocouple). Then the two thermocouples, acting in parallel, average the emf's contributed from each series circuit. Each thermocouple, in effect, when installed directly to another material, actually forms 2 equivalent measuring junctions. The analyses of the circuits in Figure 8 are given in Equations (19) and (20), and show that the results from each method will be identical.

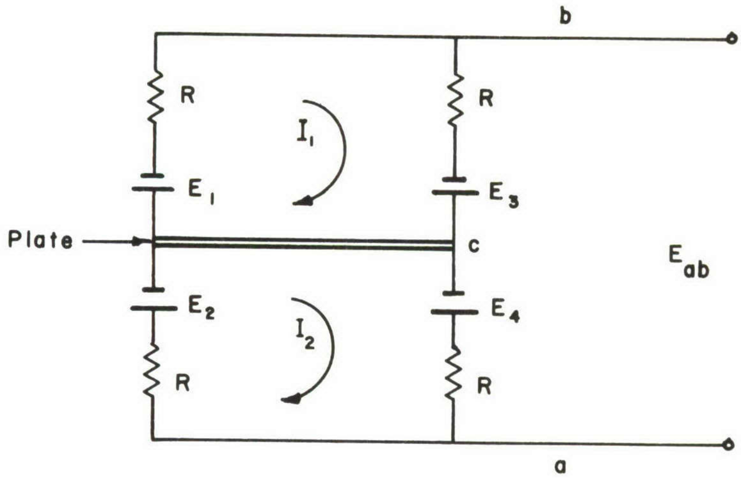


Figure 8A. Equivalent Electrical Circuit for Two Parallel Thermocouples on a Common Plate

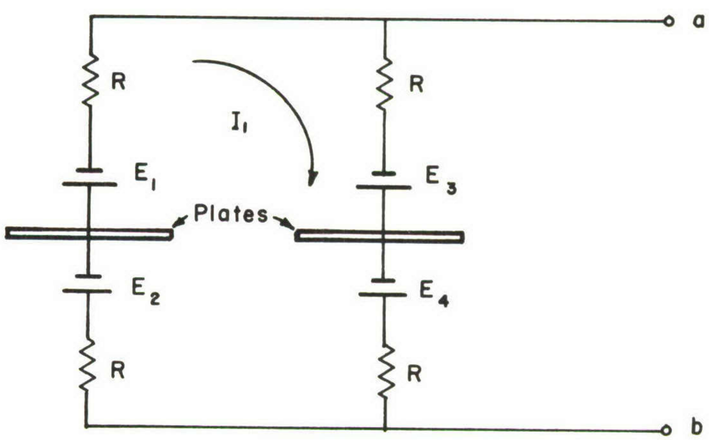


Figure 8B. Equivalent Electrical Circuit for Two Parallel Thermocouples on Separate Plates

An analysis of Figure 8A gives:

$$I_1 = \frac{E_3 - E_1}{2R} \qquad I_2 = \frac{E_4 - E_2}{2R}$$

$$E_{bc} = E_3 - \frac{(E_3 - E_1)}{2R} - R \qquad E_{ac} = E_4 - \frac{(E_4 - E_2)}{2R} -R$$

$$= \frac{2E_3 - E_3 + E_1}{2} \qquad = \frac{2E_4 - E_4 + E_2}{2}$$

$$E_{bc} = \frac{E_3 + E_1}{2} \qquad E_{ac} = \frac{E_4 + E_2}{2}$$

$$E_{ba} = E_{ba} + E_{ac}$$

Therefore,

$$E_{ba} = \frac{E_1 + E_2 + E_3 + E_4}{2} \quad . \tag{19}$$

An analysis of Figure 8B gives:

$$I_1 = \frac{E_3 + E_4 - E_2 - E_1}{4R}$$

$$E_{ab} = E_3 + E_4 - \frac{2R\,(E_3 + E_4 - E_2 - E_1)}{4R}$$

$$= \frac{2E_3 + 2E_4 - E_3 - E_4 + E_2 + E_1}{2}$$

Therefore,

$$E_{ab} = \frac{E_3 + E_4 + E_2 + E_1}{2}, \tag{20}$$

where the divisor represents the number of thermocouple installations. The results of the two analyses are therefore the same.

Whether the parallel-connected thermocouples are attached to separate plates or to a common plate is immaterial providing the plate resistance between the thermocouples can be neglected. Tests show that the resistance of several feet of thermocouple wire is sufficient to allow accurate temperature averaging. The temperature-measuring device, however, must have a floating input where more than one group of thermocouples are being averaged.

SECTION VI

EXPERIMENTAL TEST DATA AND RESULTS

Experimental tests were made using the recording instruments, radiant heat methods, and power controllers for full-scale laboratory test simulation. Each data point consisted of one thermocouple for the parallel circuit and one for recording the temperature. All tests were made with thermocouples located along one single line. Thermocouples were installed with resistance-welding equipment. These tests were made to obtain data to help verify the previous assumptions presented.

For the first test setup, seven thermocouples were spaced evenly on sheets of aluminum, steel, and titanium measuring 36 inches long, 12 inches wide, and 1/16 inch thick. For the second test, three thermocouples were located on a sheet of aluminum 20 inches long, 8 inches wide, and 1/16 inch thick, divided into three parts, cut out, and connected by a one-inch section at the center. Each section was heated separately, or in combination. Both test set-ups are shown schematically in Figure 9. Iron-constantan duplex wire was used exclusively.

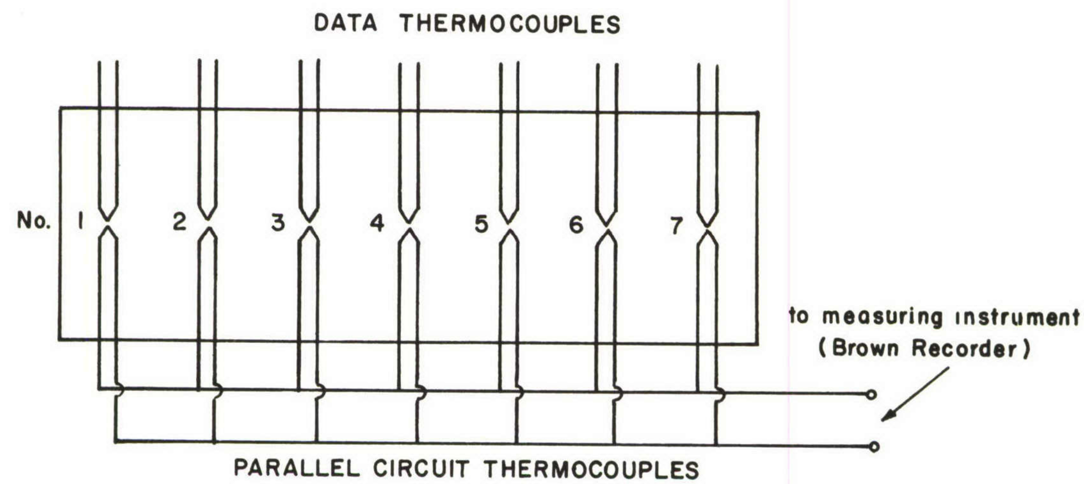


Figure 9A. Test Plate Thermocouple Arrangement for First Test Series

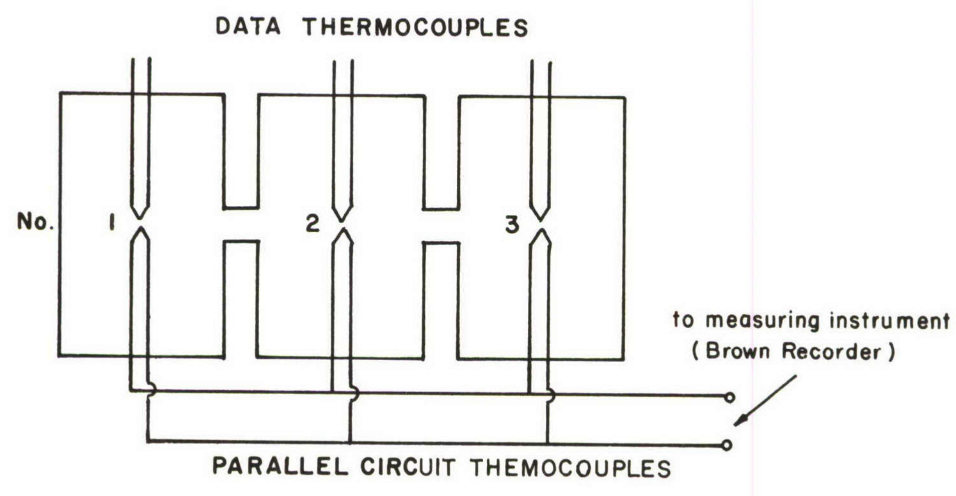


Figure 9B. Test Plate Thermocouple Arrangement for Second Test Series

Thermal conditions of equal temperatures (uniform), unequal temperatures (linear), and high rates of temperature change (transient) were simulated with radiant energy. Response rates were apparently equal between equilibrium and transient methods.

The monitor or data thermocouples were connected to individual Brown Recorders to collect temperature data at each location. The parallel circuit temperature was measured with the same type recording instrument.

Test values measured by the data thermocouples were used for a calculated average, mean T_P was calculated from Equation (9) and mean T_M was calculated from Equation (10). These values were compared with each other and with the measured temperature (electrical average T_E) of the parallel circuit. Figure 9A shows the 7 points of the complete thermocouple circuits and the electrical schematic and the recorded test data are shown in Figure 10. Other configurations for the first test series are shown in Figures 10 through 19. The uniform temperature is distributed symmetrically about the center of the test panel, and increases uniformly from each edge with the hottest point at the center. The linear temperature increases uniformly from one edge of the test panel to the opposite. The test data is within the accuracy expected from the recording instrument and the human error from reducing the test data. Data for equal temperatures at all thermocouple locations is not presented since T_E corresponds to T_M and T_P. The only error present is in the recording instrument.

Extreme examples of parallel circuits are shown in Figures 11 through 15. The materials show differences in the circulating emf's for the uniform temperature distribution. The total values of the circulating emf's for the various configurations (Figures 10 to 23) are presented as temperatures in Figure 25.

All common connections for the parallel circuits were made to terminal strips. Switching circuits were added for the second test series to facilitate adding and subtracting leads and resistances. No error is introduced from the switches or terminal strips if the temperature is equal at that point.

When a single ground wire is used, it should be located at the hottest known point. In the test results for circuits shown in Figures 11 and 12, the values for K change signs between the hot and cold locations; the basic difference between the two circuits is a change from symmetrical to unsymmetrical. In the circuit of Figure 11, the effects of plate resistance on either side are the same, while in Figure 12, the effects are all acting in one direction. Unequal thermocouple spacing changes the IR drop between one side and the other, which will alter the circulating emf's and change the calculated value of K. This type circuit, while not recommended for general use, illustrates the problems associated with paralleling grounded thermocouples.

Calculating the difference between the electrical average (T_E) and the calculated value (T_P) defines the magnitude and sign of the circulating current effect. This value or quantity is defined as:

$$T_E = T_P \pm K , \tag{19}$$

where K represents the variable term in Equation (9). The sign of K depends on the polarity. For special cases and the recommended application:

$$T_M = T_P \cdot \qquad (20)$$

The calculated value of K is a function of the magnitude and direction of the circulating current, which is determined partially by the physical properties of the materials, and possibly by thermocouple spacing.

Figures 14 and 15 show one primary center thermocouple wire removed; an iron wire was removed in Figure 15, and a constantan wire in Figure 14. Tests with this configuration show that the constantan wire is responsible for the primary emf value. When a single iron ground thermocouple wire is located at the coldest point in Figure 12, calculations from Equation (9) are not satisfactory. Comparing T_E to T_M and then to T_P in Figure 11 shows a similar deviation. The electrical signal, T_E, however, is acceptable.

Figures 16 and 17 show the effect of removing any two single thermocouple wires. The relationships between T_E, T_M, and T_P are maintained. Complete thermocouple measuring junctions are removed in Figures 18 and 19. The change in spacing gives an unbalanced electrical circuit, but the resulting change to K is small.

The second test set-up consisted of using three separate heat sources and three thermocouples connected in parallel to direct the grounding between three areas. A single plate of three rectangular sections was connected by a one-inch width of basic plate. Tests were made with the plate as a single connected unit and then as three separate units. Temperatures during test runs were controlled and maintained as nearly identical as possible between sections. Tests were made with and without grounding the supporting frame to the common building electrical ground. This data is shown in Figures 20 through 24.

Thermocouple wires were broken and resistors inserted to provide balanced and unbalanced resistance between the individual thermocouple circuits to demonstrate that individual thermocouple circuits must have equal resistances to function correctly. Where the total resistance of each circuit is high, slight unbalance can be tolerated. We installed resistors up to 500 ohms in each circuit. The resistance of a few feet of thermocouple wire is sufficient to nullify the variations in resistance at the measuring junction.

A plot of K with respect to the arithmetic mean temperature is presented in Figure 25. While circuits of unorthodox types have been presented for information, these conditions can exist when thermocouple wires break. Grounded parallel circuits are recommended only when duplex wire (insulated) is used and a complete measuring junction is included at each location. Figure 24 shows two constantan wires connected to a plate grounded to the common building ground. A thermocouple measuring circuit is formed.

Primary resistances of eight ohms resulted from the length of thermocouple wires in the first test series. One-hundred-ohm resistors were added to each circuit in the second test series, as shown in Figure 21. The best results were obtained with approximately 100 ohms resistance in each measuring junction circuit.

Constantan thermocouple wire (24 gage) used for all tests has a resistance of .727 ohms/foot, and iron thermocouple wire (24 gage) has a resistance of .148 ohms/foot.

SECTION VII

SWITCHING CIRCUITS FOR PARALLEL THERMOCOUPLES

While a parallel thermocouple circuit will provide the desired signal to control remote equipment, other arrangements are necessary to provide data for individual points. One method of accomplishing this is to provide a switching panel which combines parallel terminal strips, a standard reference junction, and a data recording instrument. If properly designed, this panel will collect data from each thermocouple. Good power control is maintained while recording individual values for temperature.

For transient heating, a pre-run is necessary for calibration at several equilibrium temperature points. At each selected temperature increment for T_E, each temperature value is recorded. A plot of T_E is made for each location and temperature for thermocouples in each control heat area or zone. Since results show that deviation between the steady state equilibrium calibration run and the actual transient simulation is insignificant transient data has not been included in this report. The relationship between T_E and individual values within the circuit is the same for heating rates up to 50°F per second.

Pre-runs of most tests are usually necessary to check the system, power distribution, temperature distributions, etc. The data sampling technique mentioned can be used or combined into this pre-run procedure.

Although a high-speed data sampling and handling system can be used during transient heat simulation, such a system is complex and the capability is compromised. Although equipment has been designed specifically for this purpose it is very expensive, and the method described serves most requirements. Once the individual temperatures are known, the same controls will give identical temperature distribution from any single thermocouple in the area.

SECTION VIII

CONCLUSIONS

Any number of thermocouple measuring junctions can be attached to a common base material and yield an average electrical signal. Proper instrument calibration for the given thermocouple materials will give the same signal as a single thermocouple at a temperature identical to the average signal from a parallel circuit. The effects of circulating emf's between thermocouples cancel each other in most common circuits, and in most others the effect is insignificant.

This method of thermal simulation provides a very useful tool for structural testing of full-scale flight vehicles and provides useful and accurate representative feedback signals for remote control of power regulating equipment. Since T_s is the only true test parameter in heat balance, Equations (1) and (2), the parallel average signal is representative of the temperature of each heated area.

REFERENCES

1. Boggs, B. C. High Temperature Tension Patch and Thermal Simulation Methods for Structural Testing, Section III, Wright Air Development Division, WPAFB, Ohio, WADD TR 60-235, 1960.

OTHER REFERENCE MATERIAL

2. Korn, G. A., Electronic Analog Computer, Page 12, McGraw-Hill Book Co., Inc., Second Ed., 1956.

3. Sine, J. B., Ritchey, B. B., and Vogelsand, C. A., "Current From Temperature," Instrumentation, Minneapolis-Honeywell, Minneapolis, Minnesota.

4. Dawes, C. L., Electrical Engineering--DC Current, Page 71, Third Ed., McGraw-Hill Book Co., Inc., 1937.

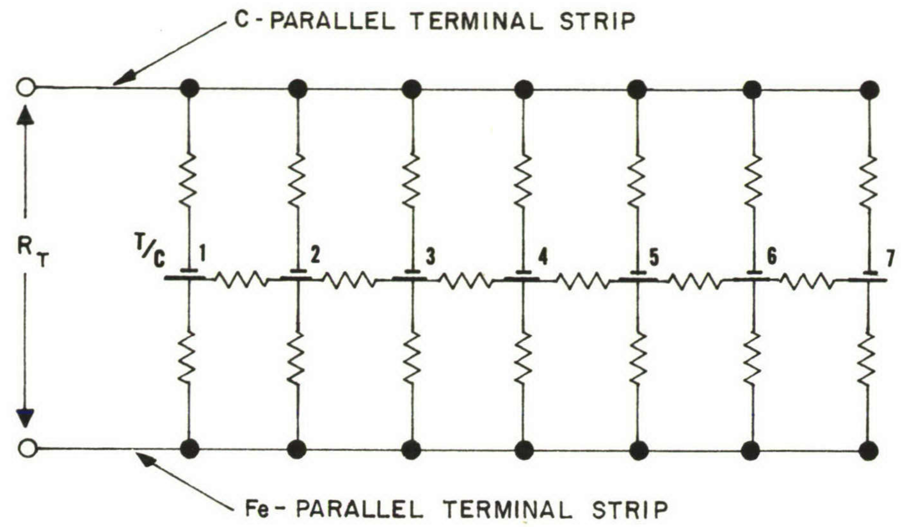
5. GE Computer Manual for WADD, General Electric Company, Phoenix, Arizona.

APPENDIX

SCHEMATICS AND RESULTS OF TESTS

Tests were conducted on a number of different circuit configurations with different plate materials and different thermal conditions. The results of the tests are tabulated and shown with the pertinent circuit configuration. Values shown for T_E are those recorded in the parallel wires; T_M was calculated from Equation (10); and T_P was calculated from Equation (9). Figure 25 shows the total values of the circulating emf's for all configurations plotted as temperatures.

Two thermocouples were installed at each location; one was connected into the parallel circuit and one was used for individual temperature recordings. All indicated test temperatures were recorded in degrees Fahrenheit from the individual thermocouples. The metal shown for each test indicates the plate metal, and (U) indicates uniform thermal conditions and (L) indicates linear thermal conditions.



Test A. Aluminum (U)

T/C#	1	2	3	4	5	6	7	T_E	T_M	T_P	K
Temp.	98	96	95	100	95	90	91	97	95	95	+2
	190	187	186	200	174	175	160	184	182	182	+2
	275	280	280	300	260	254	223	270	267	267	+3
	355	367	372	400	340	329	284	352	350	350	+2
	431	455	465	500	418	401	343	432	430	430	+2

Test B. Aluminum (L)

	1	2	3	4	5	6	7	T_E	T_M	T_P	K
	78	87	100	100	97	94	94	96	93	93	+3
	91	145	205	200	195	192	175	179	172	172	+7
	111	201	302	300	289	280	249	256	247	247	+9
	135	262	398	400	383	365	316	333	323	323	+10
	152	320	505	500	475	455	390	412	400	400	+12

C = Constantan Wire

Fe = Iron Wire

Test C. Steel (U)

T/C#	1	2	3	4	5	6	7	T_E	T_M	T_P	K
Temp.	98	94	96	99	94	87	96	95	95	95	-
	175	182	169	193	170	160	172	175	174	174	+1
	246	265	236	286	243	229	244	250	250	250	-
	312	345	303	375	312	293	310	320	321	321	-1
	376	419	368	460	377	354	372	389	389	389	-
	436	488	429	540	440	412	430	454	454	454	-
	490	552	486	616	500	468	482	513	513	513	-
	530	598	529	672	544	510	522	558	558	558	-

Test D. Steel (L)

	1	2	3	4	5	6	7	T_E	T_M	T_P	K
	87	105	110	104	111	101	100	102	102	102	-
	115	240	297	245	291	260	235	243	240	240	+3
	145	360	466	375	445	397	354	370	363	363	+7
	172	470	622	495	585	519	462	485	475	475	+10
	200	567	760	600	705	625	558	585	574	574	+11
	221	635	850	675	782	697	624	653	641	641	+12

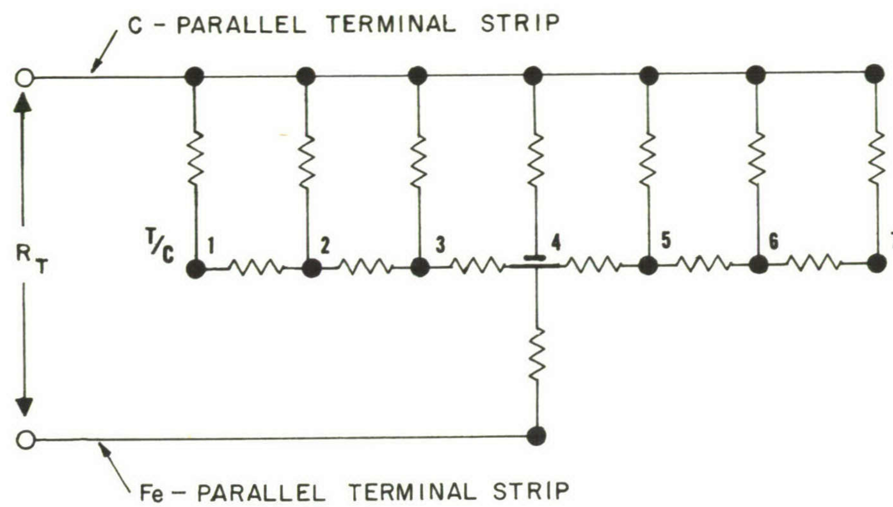
Test E. Titanium (U)

	1	2	3	4	5	6	7	T_E	T_M	T_P	K
	109	112	105	115	112	95	103	113	107	107	+6
	266	285	252	320	270	238	244	274	268	268	+6
	400	435	380	509	410	362	366	413	409	409	+4
	524	573	502	685	544	482	482	550	542	542	+8
	600	660	584	792	604	561	556	632	622	622	+10

Test F. Titanium (L)

	1	2	3	4	5	6	7	T_E	T_M	T_P	K
	89	104	108	107	116	105	102	107	104	104	+3
	107	215	286	260	290	267	222	241	235	235	+6
	125	310	447	392	440	406	326	355	349	349	+6
	142	400	603	518	575	536	424	465	457	457	+8
	157	487	750	634	695	651	515	565	556	556	+9
	173	592	886	762	800	754	600	655	651	651	+4
	182	610	951	789	850	802	645	699	690	690	+9

Figure 10. Basic Parallel Electrical Circuit with 7 Thermocouples (Common)



Test A. Aluminum (U)

T/C#	1	2	3	4	5	6	7	T_E	T_M	T_P	K
Temp.	101	98	95	100	95	94	93	100	96	99	+1
	192	191	185	200	178	178	162	190	183	192	-2
	274	284	281	300	264	260	227	277	270	285	-8
	356	373	372	400	343	335	289	361	352	376	-15
	437	467	470	500	425	410	351	446	437	469	-23
	501	551	565	600	513	482	408	526	517	559	-33
	573	685	659	700	566	553	466	603	600	650	-47

Test B. Aluminum (L)

	1	2	3	4	5	6	7	T_E	T_M	T_P	K
	80	89	100	100	100	99	98	98	95	98	0
	91	146	208	200	200	200	180	183	175	188	-5
	106	202	310	300	295	291	257	265	252	276	-11
	126	258	404	400	388	378	329	343	326	363	-20
	145	315	505	500	482	465	399	420	402	452	-32

Test C. Steel (U)

T/C#	1	2	3	4	5	6	7	T_E	T_M	T_P	K
Temp.	191	184	183	200	168	175	155	180	179	189	-9
	281	271	274	300	242	255	224	265	263	282	-17
	364	352	355	400	310	332	290	348	343	372	-24
	444	434	443	500	386	411	357	430	425	463	-33
	524	515	527	600	458	488	425	512	505	553	-41
	605	595	615	700	532	567	495	595	587	644	-49
	685	680	709	800	613	650	568	681	672	736	-55

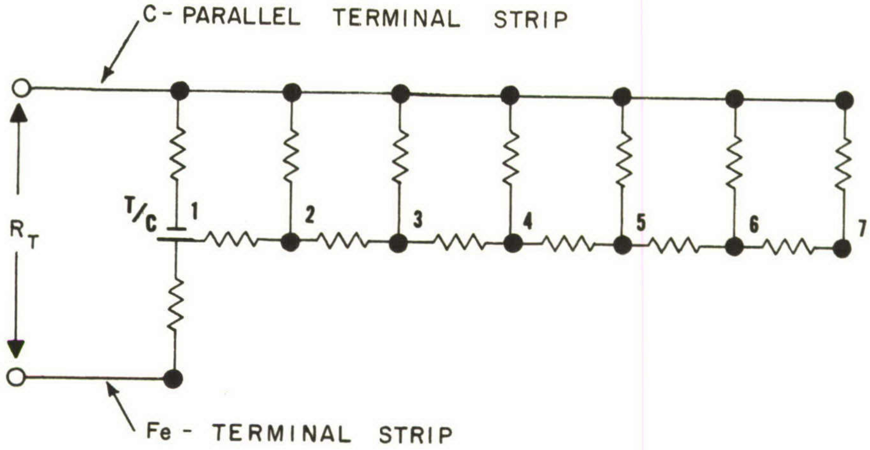
Test D. Steel (L)

	1	2	3	4	5	6	7	T_E	T_M	T_P	K
	84	94	105	100	100	96	90	98	96	98	0
	96	162	231	200	208	204	160	187	179	189	-2
	106	230	298	300	306	296	219	272	251	286	-14
	120	302	473	400	411	400	288	360	342	371	-11
	138	367	582	500	504	495	355	444	420	460	-16
	160	433	686	600	600	580	425	523	498	549	-26
	190	508	785	700	692	671	496	605	577	639	-34
	210	587	910	800	790	769	569	692	664	732	-40

Test E. Titanium (U)

	1	2	3	4	5	6	7	T_E	T_M	T_P	K
	111	111	109	121	110	101	104	115	110	115	0
	274	280	268	324	261	248	241	280	271	297	-17
	410	428	403	502	390	370	354	416	409	455	-39
	528	550	521	660	504	481	455	530	528	594	-64

Figure 11. Symmetrical Parallel Electrical Circuit with 7 Constantan and 1 Iron Thermocouple Wires (Common)



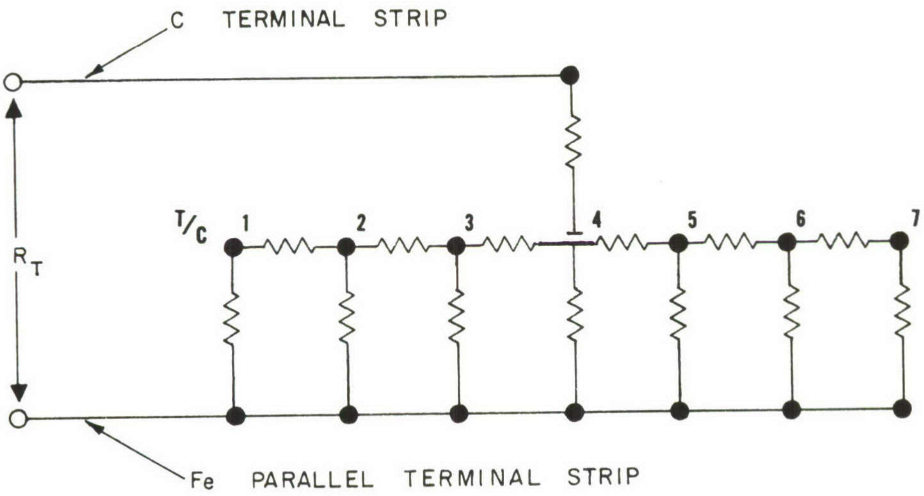
Test A. Aluminum (U)

T/C#	1	2	3	4	5	6	7	T_E	T_M	T_P	K
Temp.	99	96	95	100	96	93	93	97	96	95	+2
	190	189	186	200	180	178	163	181	183	173	+8
	274	280	280	300	262	255	224	262	268	246	+16
	354	369	373	400	341	330	285	342	350	318	+24
	433	460	466	500	421	405	346	425	433	390	+35

Test B. Aluminum (L)

	1	2	3	4	5	6	7	T_E	T_M	T_P	K
	87	92	99	100	102	98	99	100	97	92	+8
	96	147	208	200	200	201	181	185	176	136	+49
	110	203	306	300	295	292	259	265	252	181	+84
	125	260	413	400	392	384	333	346	330	228	+118
	146	318	510	500	485	470	404	424	405	276	+148

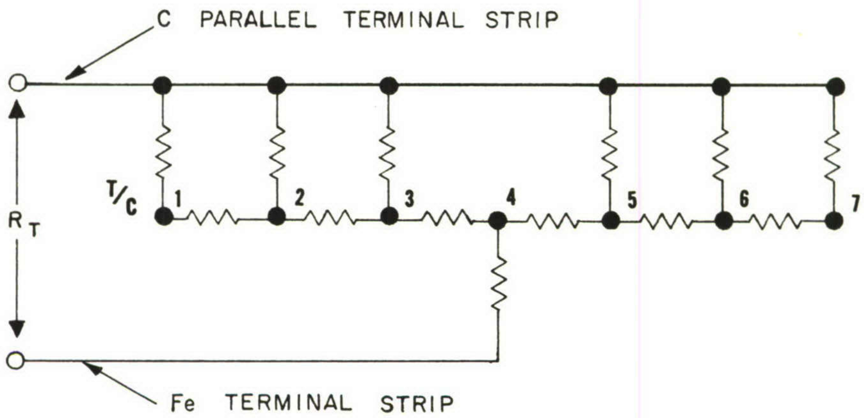
Figure 12. Unsymmetrical Parallel Electrical Circuit with 7 Constantan and 1 Iron Thermocouple Wires (Common)



Test A. Titanium (U)

T/C#	1	2	3	4	5	6	7	T_E	T_M	T_P	K
Temp.	110	106	100	111	107	98	101	122	105	108	+14
	270	277	259	315	258	242	238	334	265	290	+44
	405	422	393	495	387	365	351	517	403	449	+68
	523	549	512	655	500	475	452	675	524	589	+86

Figure 13. Parallel Electrical Circuit with 1 Constantan and 7 Iron Thermocouple Wires (Common)



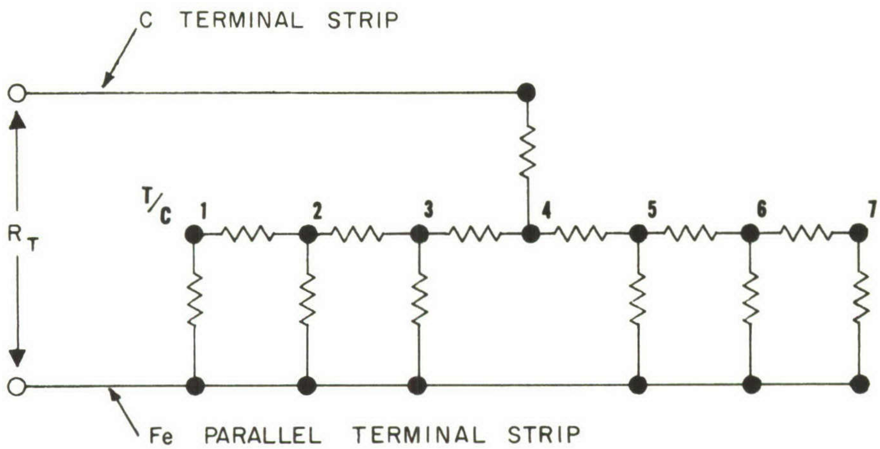
Test A. Steel (U)

T/C#	1	2	3	4	5	6	7	T_E	T_M	T_P	K
Temp.	95	100	97	100	100	95	100	98	98	99	-1
	216	247	240	250	250	240	245	240	241	245	-5
	303	346	335	350	346	336	352	336	338	343	-7
	394	444	430	450	450	440	461	436	438	444	-8
	499	553	530	550	550	543	575	545	543	546	-1
	599	651	631	650	653	649	690	649	646	648	+1
	700	755	730	750	751	750	797	751	748	749	+2

Test B. Steel (L)

	1	2	3	4	5	6	7	T_E	T_M	T_P	K
	78	77	78	82	79	76	80	73	78	80	-7
	80	115	205	200	180	200	166	150	163	179	-29
	85	170	369	365	310	355	286	260	277	314	-54
	90	220	520	510	430	490	395	367	379	434	-67
	95	365	656	640	535	607	490	445	469	541	-96
	100	308	780	757	630	710	580	520	552	638	-118
	105	342	874	846	705	786	647	582	615	712	-130
	109	365	913	890	745	819	683	614	646	748	-134

Figure 14. Parallel Electrical Circuit with 6 Constantan and 1 Iron Thermocouple Wires (Common)



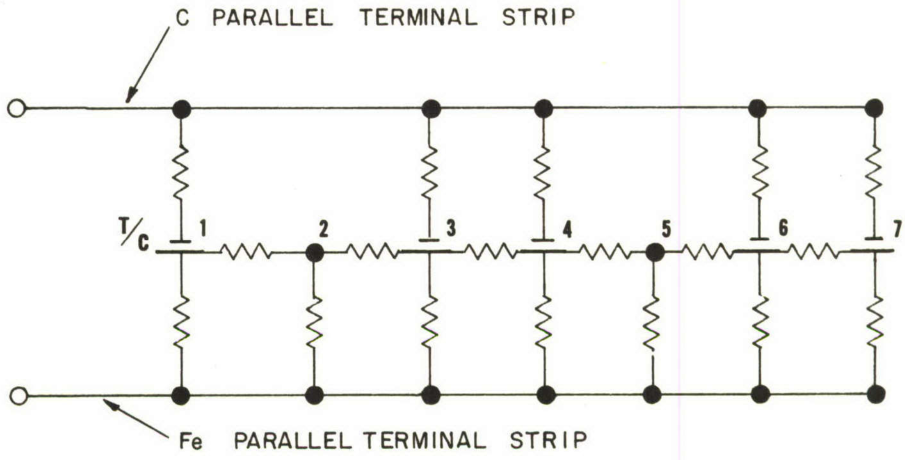
Test A. Steel (U)

T/C#	1	2	3	4	5	6	7	T_E	T_M	T_P	K
Temp.	95	100	97	100	100	95	100	100	98	99	+1
	216	247	240	250	250	240	245	250	241	245	+5
	303	346	335	350	346	336	352	354	338	343	+11
	394	444	430	450	450	440	461	452	438	444	+8
	499	553	530	550	550	543	575	555	543	546	+9
	599	651	631	650	653	649	690	655	646	648	+7
	700	755	730	750	751	750	797	755	748	749	+6

Test B. Steel (L)

	1	2	3	4	5	6	7	T_E	T_M	T_P	K
	78	77	78	82	79	76	80	75	78	80	-5
	80	115	205	200	180	200	166	195	163	179	+16
	85	170	369	365	310	355	286	360	277	314	+46
	90	220	520	510	430	490	395	505	379	434	+71
	95	265	656	640	535	607	490	640	469	541	+99
	100	308	780	757	630	710	580	755	552	638	+117
	105	342	874	846	705	786	647	848	615	712	+136
	109	365	913	890	745	819	683	890	646	748	+142

Figure 15. Parallel Electrical Circuit with 1 Constantan and 6 Iron Thermocouple Wires (Common)



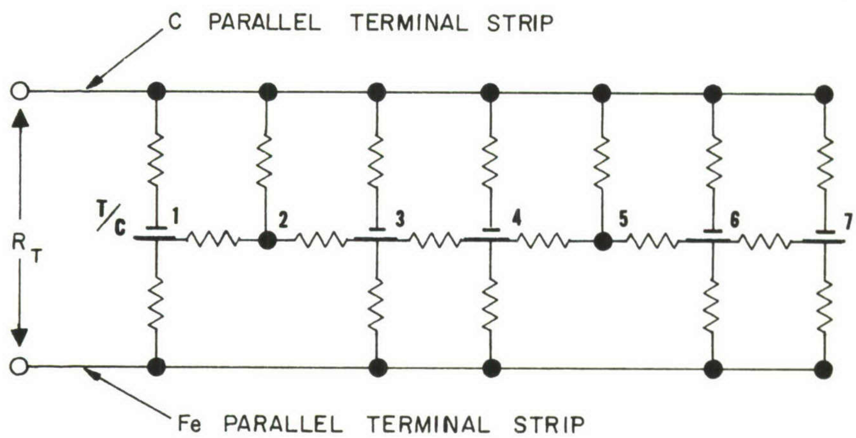
Test A. Aluminum (U)

T/C#	1	2	3	4	5	6	7	T_E	T_M	T_P	K
Temp.	76	75	72	77	75	70	76	76	74	74	+2
	169	168	155	189	150	157	153	161	164	164	-3
	265	268	245	306	234	242	231	255	258	257	-2
	356	363	330	415	311	318	302	340	344	343	-3
	412	430	393	490	367	371	350	404	403	403	+1

Test B. Aluminum (L)

	1	2	3	4	5	6	7	T_E	T_M	T_P	K
	87	87	124	117	127	121	112	115	112	113	+2
	100	170	245	203	235	221	190	200	192	195	+5
	112	274	358	286	335	307	262	276	265	270	+6
	125	368	464	364	425	386	330	349	333	340	+9
	137	432	555	434	504	454	390	412	394	402	+10

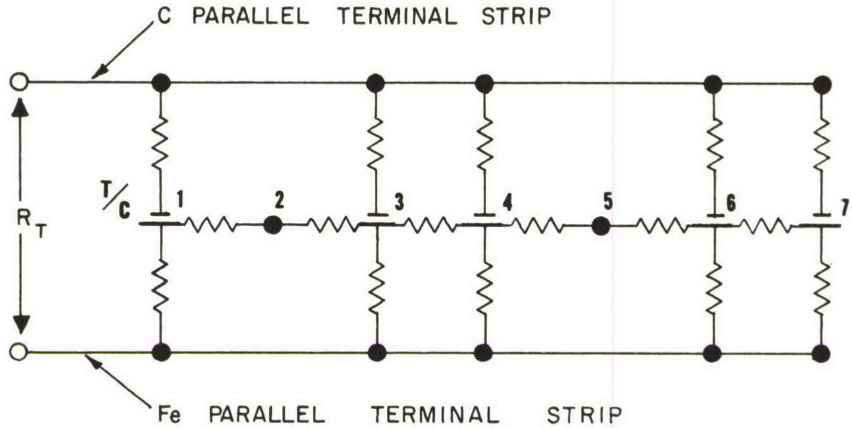
Figure 16. Parallel Electrical Circuit with 5 Constantan and
7 Iron Thermocouple Wires (Common)



Test A. Aluminum (U)

T/C#	1	2	3	4	5	6	7	T_E	T_M	T_P	K
Temp.	75	73	71	75	73	70	73	75	73	73	+2
	162	165	150	181	145	154	145	160	158	158	+2
	259	266	240	300	229	237	224	252	252	251	+3
	345	360	325	407	305	314	295	340	337	336	+4
	408	428	389	485	340	369	346	401	399	398	+3

Figure 17. Parallel Electrical Circuit with 7 Constantan and 5 Iron Thermocouple Wires (Common)



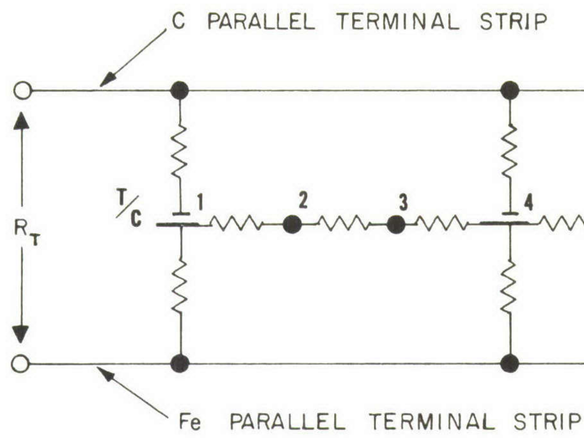
Test A. Titanium (U)

T/C#	1	2	3	4	5	6	7	T_E	T_M	T_P	K
Temp.	116		102	114		100	103	112	107	107	+5
	270		248	315		240	245	270	264	264	+6
	395		371	494		360	363	406	397	397	+9
	515		490	664		477	475	533	524	524	+9
	596		576	782		560	555	620	614	614	+6

Test B. Titanium (L)

	1	2	3	4	5	6	7	T_E	T_M	T_P	K
	87		120	118		109	104	112	108	108	+4
	106		309	269		273	227	246	237	237	+9
	124		478	400		413	331	361	349	349	+12
	140		638	525		543	430	468	455	455	+13
	155		775	635		654	519	560	548	548	+12
	165		841	693		711	608	608	596	596	+12

Figure 18. Parallel Electrical Circuit with 5 Thermocouples (Common)



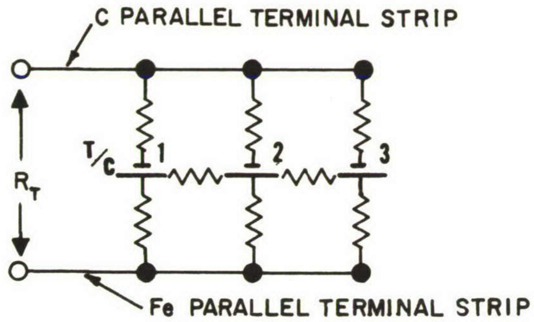
Test A. Aluminum (U)

T/C#	1	2	3	4	5	6	7	T_E	T_M	T_P	K
Temp.	109			121			117	110	116	116	-6
	188			235			203	205	209	209	-4
	261			344			283	295	296	296	-1
	324			440			350	375	371	371	+4

Test B. Aluminum (L)

	1	2	3	4	5	6	7	T_E	T_M	T_P	K
	80			133			109	103	107	107	-4
	93			192			185	169	157	157	+12
	106			274			258	228	213	213	+15
	120			350			325	285	265	265	+20
	132			422			385	336	313	313	+23
	143			475			430	375	349	349	-26

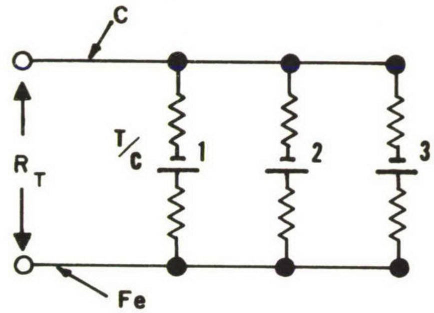
Figure 19. Parallel Electrical Circuit with 3 Thermocouples (Common)



A

Basic Circuit
Plate Not Separated

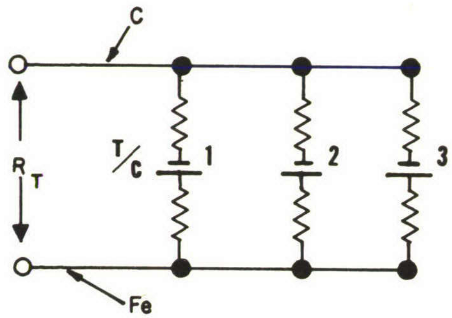
T/C#	1	2	3	T_E	T_M	T_P	K
Temp.	79	90	85	85	85	85	0
	79	215	164	151	152	152	-1
	79	303	222	200	201	201	-1
	81	367	265	235	236	236	-1
	85	399	290	256	258	258	-2



B

Plate Separated,
Not Insulated

1	2	3	T_E	T_M	T_P	K
77	87	80	81	81	81	0
77	173	141	127	130	130	-3
77	243	192	166	171	171	-5
77	354	273	229	235	235	-6
77	396	303	252	259	259	-7

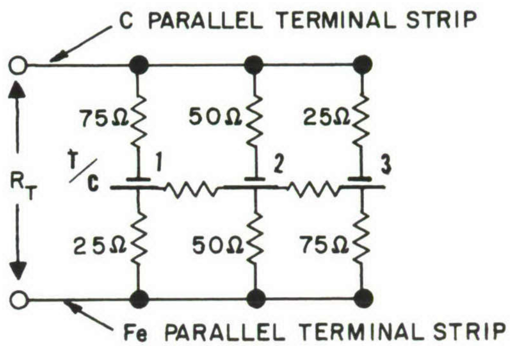


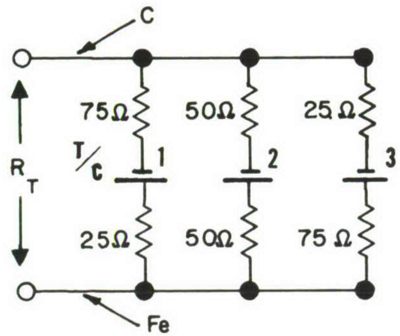
C

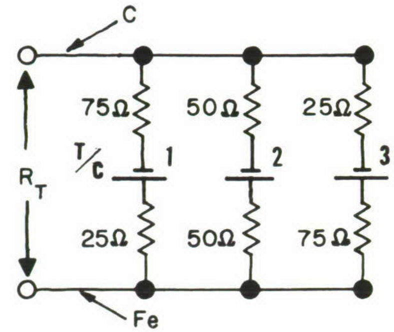
Plate Separated
and Insulated

1	2	3	T_E	T_M	T_P	K
76	86	80	80	81	81	-1
76	184	148	134	136	136	-2
76	255	200	174	177	177	-3
76	314	242	207	211	211	-4
76	351	268	228	232	232	-4

Figure 20. Basic Parallel Electrical Circuit with 3 Thermocouples (Common) Without Additional Resistors, Aluminum Plate







A

Basic Circuit
Plate Not Separated

T/C#	1	2	3	T_E	T_M	T_P	K
Temp.	76	84	78	80	79	79	+1
	76	207	159	149	147	147	+2
	76	295	217	199	196	196	+3
	79	359	260	236	233	233	+3
	84	395	286	260	253	253	+7

B

Plate Separated,
Not Insulated

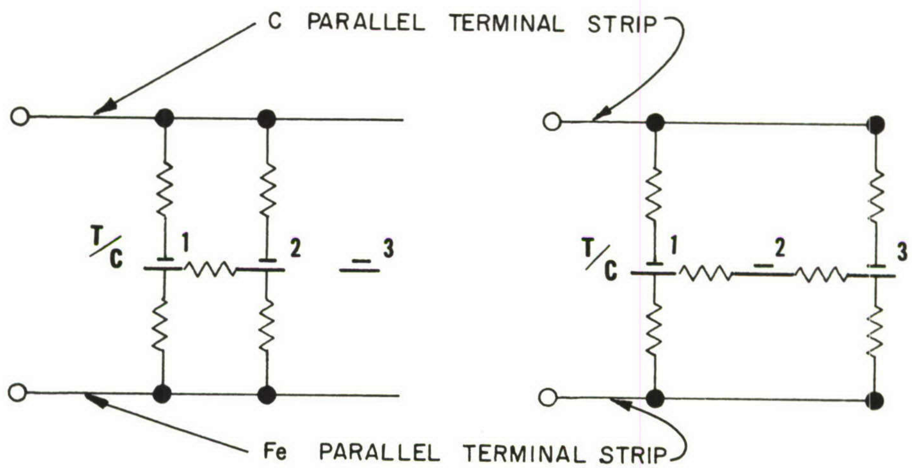
1	2	3	T_E	T_M	T_P	K
78	95	85	85	86	86	-1
78	170	140	130	129	129	+1
78	221	181	160	160	160	0
78	315	252	215	215	215	0
78	374	292	247	248	248	-1

C

Plate Separated
and Insulated

1	2	3	T_E	T_M	T_P	K
78	93	85	84	85	85	-1
78	184	146	135	136	136	+1
78	256	198	177	177	177	0
78	319	242	215	213	213	+2
78	373	280	245	244	244	+1

Figure 21. Parallel Electrical Circuit with 3 Thermocouples, Resistors Added, Aluminum Plate (Common)



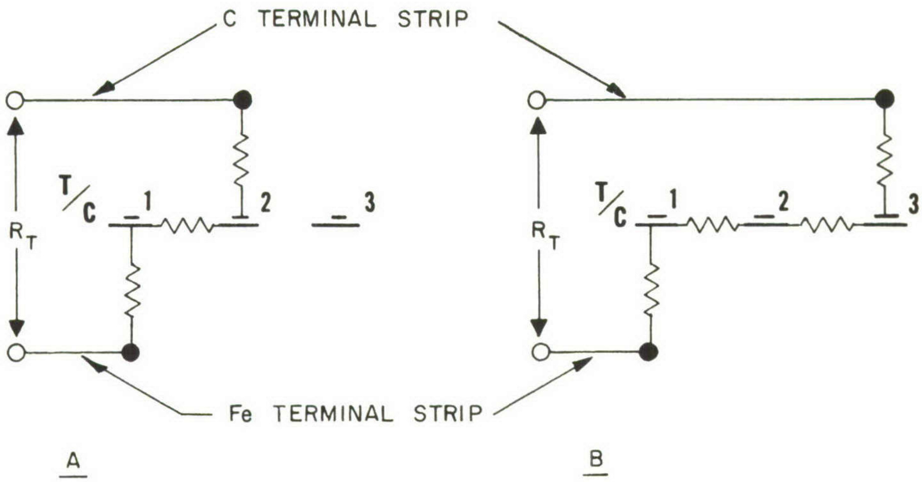
A

B

T/C#	1	2	3	T_E	T_M	T_P	K
Temp.	77	83	74	79	80	80	-1
	77	159		115	118	118	-3
	78	216		144	147	147	-3
	79	265		170	172	172	-2
	80	308		193	194	194	-1
	83	345		212	214	214	-2
	85	373		227	229	229	-2
	88	392	81	238	240	240	-2

1	2	3	T_E	T_M	T_P	K
78	80	74	76	76	76	0
78		74	76	76	76	0
78		74	76	76	76	0
78		74	77	76	76	+1
80		75	79	78	78	+1
82		77	80	80	80	0
85		79	83	82	82	+1
88	395	81	85	85	85	0

Figure 22. Parallel Electrical Circuits for 2 Thermocouples (Common) Aluminum Plate



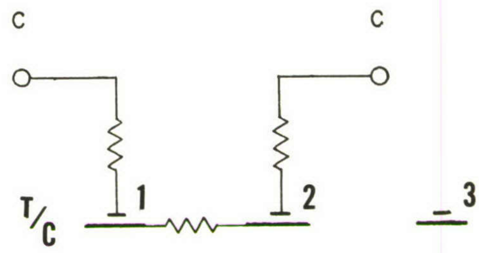
A

T/C#	1	2	3	T_E	T_M	T_P	K
Temp.	86	89	80	85	87	87	-2
	86	165	80	142	126	126	+16
	86	222	80	186	154	154	+32
	86	273	80	229	180	180	+49
	88	315	81	264	202	202	+62
	90	352	83	294	221	221	+73
	93	377	85	318	235	235	+83
	96	396	86	335	246	246	+89

B

1	2	3	T_E	T_M	T_P	K
79	83	76	77	77	77	0
79	163	76	79	78	78	+1
80	223	76	80	78	78	+2
81	276	77	81	79	79	+2
84	321	79	83	82	82	+1
87	356	80	85	84	84	+1
90	383	82	87	86	86	+1
92	398	85	89	89	89	0

Figure 23. Electrical Circuit for 1 Thermocouple, Wires Separated (Common) Aluminum Plate



(Linear)

1	2	3	T_E	T_M	T_P	K
140	400	125	292	270	270	+22
150	400	135	283	275	275	+ 8

Figure 24. Measuring Circuit with Two Constantan Wires Forming a Junction on Aluminum Plate (Common)

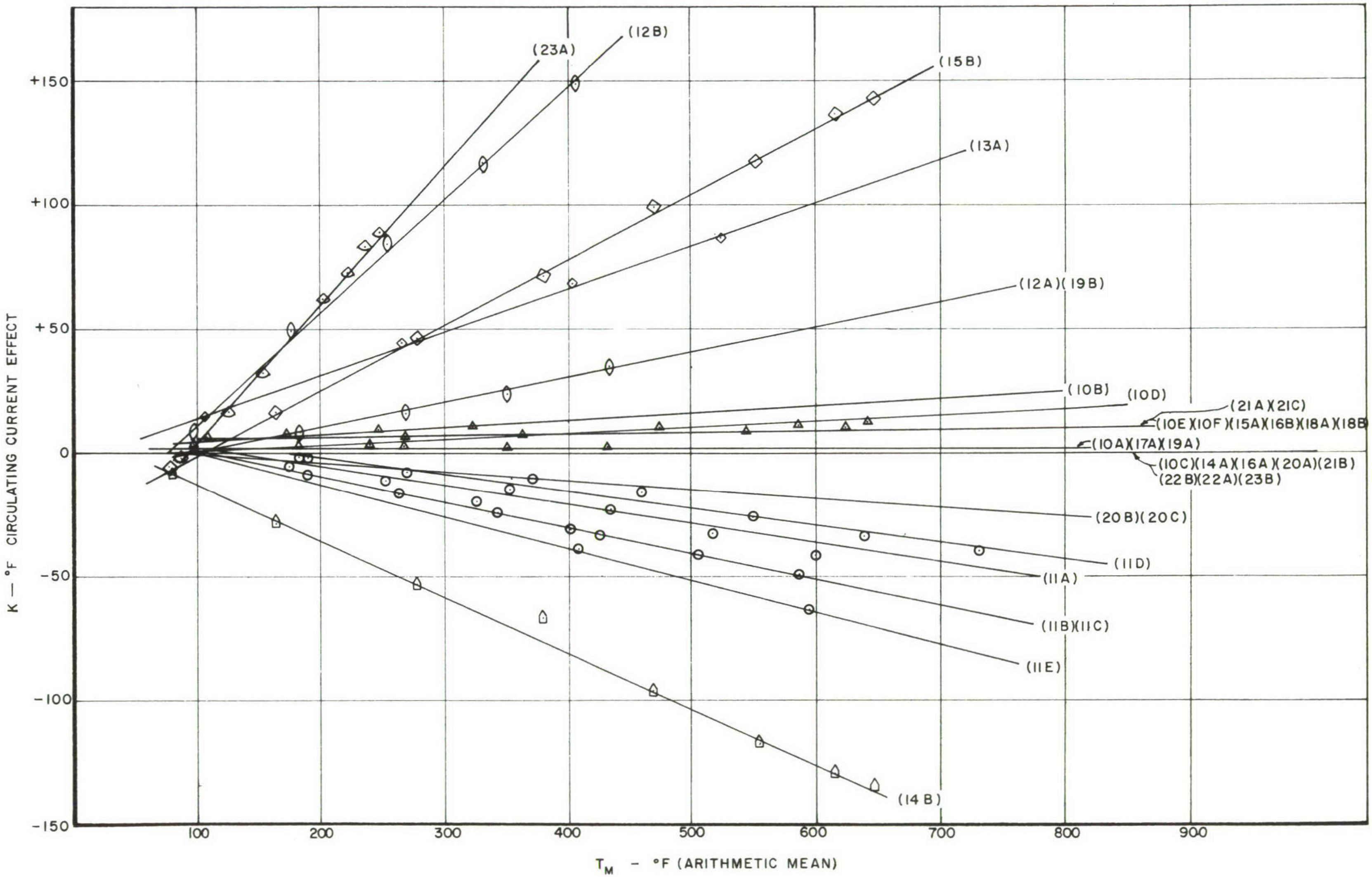


Figure 25. Parallel Grounded Thermocouple Circuit Constant for Circulating emf's